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Glaciochemical records from a Mt. Everest ice core: relationship to atmospheric circulation over Asia

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Abstract

Glaciochemical records recovered from an 80.4 m ice core in the East Rongbuk (ER) Glacier (elevation: 6450 m) on the northern slope of Mt. Everest provide a reconstructing of past climate for the period AD 1846–1997. Empirical orthogonal function (EOF) analysis on the eight major ion (SO_4^{2-}, Mg^{2+}, Ca^{2+}, Na^+, Cl^-, NH_4^+, K^+, and NO_3^-) time-series reveals inter-species relations and common structure within the ER glaciochemical data. The first two EOF series (EOF1-ions and EOF2-ions) are compared with instrumental data of sea level pressure (SLP) to demonstrate that the EOF-ions series display strong connections to winter (January) and summer (July) SLP over the Mongolian region. The positive relationship between EOF1-ions and the Mongolian High (MongHi) series suggests that enhanced winter MongHi strengthens the transport of dust aerosols southward from arid regions over central Asia to Mt. Everest. The close correspondence between EOF2-ions and the summer Mongolian Low (MongLow) indicates that the deeper MongLow, which is related to the stronger Indian Monsoon, contributes to a decrease in summer dust aerosols. Therefore, the ER ice core record comprises two assemblages of crustal species, each transported from different source regions during different seasons. EOF1-ions represents the majority of the crustal species and is related to winter atmospheric circulation patterns. These species are mainly transported from arid regions of central Asia during the winter dry season. EOF2-ions represents crustal species transported by summer atmospheric circulation from local/regional sources in the northern and southern Himalayas.

Keywords: Major ions; Ice core; Dust aerosols; Sea level pressure; Mt. Everest

1. Introduction

Glaciers of high Asia (Fig. 1) are sensitive indicators of climate change and are natural archives of variations in atmospheric processes. Chemical and physical analyses of ice cores recovered from judiciously selected accumulation zones of Asian glaciers/ice caps not only hold great potential for the development of detailed, high-resolution paleoclimate and environmental records (Mayewski et al., 1984; Thompson et al., 1989, 1997, 2000; Yao and Thompson, 1992; Yao et al., 1995; Kang et al., 2001a, b), but also can examine possible climatic forcings such as greenhouse gases and changes in solar activity (Duan et al., 2000), as well as provide information on atmospheric circulation such as responses to climatic change and change in the strength of the summer Indian Monsoon (Mayewski et al., 1983, 1984; Qin et al., 2000).

Since the 1980s, high resolution glaciochemical records have been recovered from glaciers in a variety

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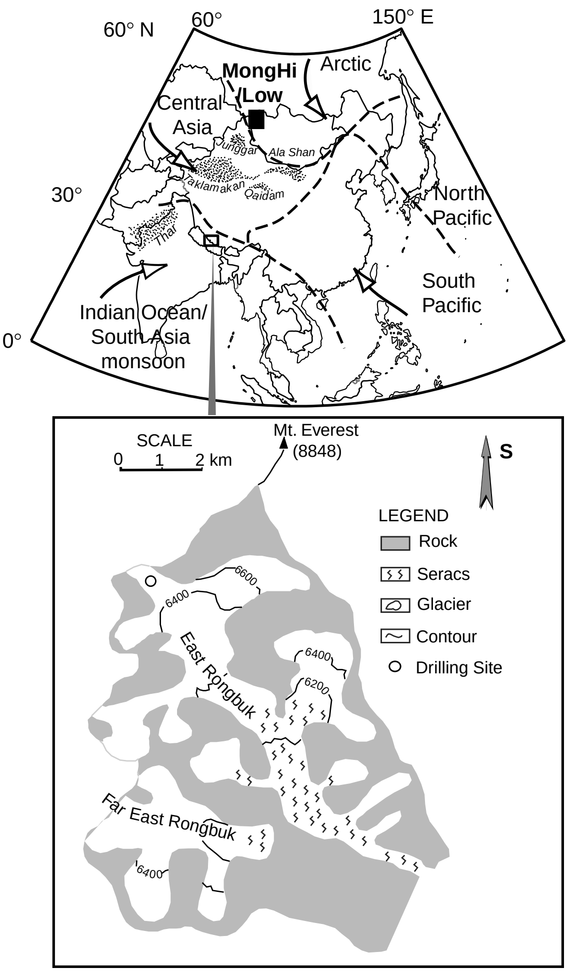


Fig. 1. Top: Location map for the East Rongbuk (ER) ice core, Mt. Everest, Tibetan Plateau, and area (blackened) of instrumental data of sea level pressure used to compare with ER ice core glaciochemical records. MongHi and MongLow refer to the winter Mongolian High and summer Mongolian Low, respectively. Also shown are schematic representations of air mass boundaries taken from Bryson (1986) and major desert regions over Asia. Bottom: The ER ice core drilling site at an elevation of 6450 m on Mt. Everest.

of mountain regions in central Asia (Mayewski et al., 1981, 1984; Lyons and Mayewski, 1983; Lyons et al., 1991; Wake et al., 1990, 1993, 1994a, b; Thompson et al., 1989, 1990; Williams et al., 1992; Kang et al., 2000, 2001a, b; Kreutz and Sholkovitz, 2000; Kreutz et al., 2001). These regional glaciochemical surveys clearly illustrate the systematic geographic distribution of major ions in snow/ice throughout the mountains of central Asia. Dust derived from the arid regions of central Asia (i.e., western China, northwestern India, etc., Fig. 1) dominates the spatial and seasonal variation of snow and aerosol chemistry in this region. Glaciers which lie adjacent to large arid regions, such as those on the northern margins of the Tibetan Plateau, display very high ionic burdens and particle concentrations due to the influx of dust derived from local sources. Aridification and dust storms are hazards to agriculture and ecosystem health. The history of these events can be investigated through ice cores.

The meteorological and pluviometric regime of the Asian continent is mainly controlled by polar air masses from the Arctic, continental air masses from central Asia, and maritime air masses from the Pacific and Indian Ocean (Fig. 1) (Bryson, 1986). The location of the East Rongbuk (ER) Glacier on Mt. Everest (27°59′N, 86°55′E) (Fig. 1) at the boundary of the South Asian Monsoon (Indian Monsoon) and the continental climate of central Asia, combined with the high elevation of the site (6450 m, well above the influence of the boundary layer), provide a unique opportunity to describe and understand change in climate and chemistry of the atmosphere over Asia.

In August 1998, an 80.4 m ice core was recovered from the ER glacier at an elevation of 6450 m on the northern slope of Mt. Everest, Tibetan Plateau (Fig. 1). Preliminary results for δ^{18}O and major ion records are reported by Qin et al. (2002). In this paper, an empirical orthogonal function (EOF) analyses (Meeker et al., 1995) is performed on major ion time-series of the ice core to investigate the existence of common structure within the ice core glaciochemical data. Associations between glaciochemical series and instrumental sea level pressure (SLP) are explored over Asia to examine the relationships between ice core records and atmospheric circulation and to investigate the climatic and environmental implications of glaciochemical records in the Mt. Everest region.

2. Ice core major ion time-series

Extreme care was taken at all times during sample collection and handling to assure that samples were not contaminated. For example, non-particulating suits, polyethylene gloves, and masks were worn at all times during sampling. The ice core was sectioned at intervals between 3.5 and 5 cm (total of 1816 samples). After sectioning the core, each sample had its outer 2 cm scraped using a clean stainless steel scalpel. Once scraped, samples were placed into pre-cleaned high-density polyethylene containers for analysis of major ions and δ^{18}O. Meanwhile, scraped ice chips were collected for β-activity measurements. Oxygen isotope analysis was performed using a Finnigan MAT-252 Spectrometer (accuracy of 0.05%) in the Laboratory of Ice Core and Cold Regions Environment, Chinese Academy of Sciences. Analysis for major ion (Na^+, K^+, Mg^{2+}, NH_4^+, Ca^{2+}, Cl^-, SO_4^{2-}, and NO_3^-) were performed using a Dionex Ion Chromatograph model

2010 (detailed methods described by Buck et al. (1992)), and the β-activity samples were filtered two times through cation exchange filters and analyzed by a gas-flow proportional counter in the Climate Change Research Center, University of New Hampshire and the Institute for Quaternary and Climate Studies, University of Maine.

Distinct seasonal variations in stable isotopes and chemical species in snow over the higher mountains of the central Himalayas are reported by several researchers authors (e.g. Wushiki, 1977; Lyons et al., 1991; Kang et al., 2000; Thompson et al., 2000). At the col of ER glacier, the average annual net balance is about 500 mm water equivalent as determined from snowpits and by measurement of a stake accumulation network established during a reconnaissance survey in May 1998. The high annual accumulation allows preservation of distinct seasonal cycles in chemical species (Fig. 2). Annual layer counting was performed by identifying seasonal cycles of $\delta^{18}O$ in association with several chemical species such as NH_4^+, Ca^{2+}, SO_4^{2-}, Mg^{2+} and verified based on calibration with known nuclear bomb horizons (1954 and 1963) identified in the well-preserved total β-activity profile from this core (Fig. 2). We counted 152 annual layers back through the entire 80.4 m ice core, indicating that our record spans the time period AD 1846–1997 (at a resolution of 12 samples per year). Our dating is further verified by the presence of a distinct spike in Cl^- concentration (marked in Fig. 4) that occurs in AD 1877 (at 64 m depth in the ice core). This spike corresponds to the monsoon failure that resulted in devastating Indian droughts in 1876–1877. This phenomenon is also observed in the Dasuopu ice core (which is about 100 km away from Mt. Everest) (Thompson et al., 2000).

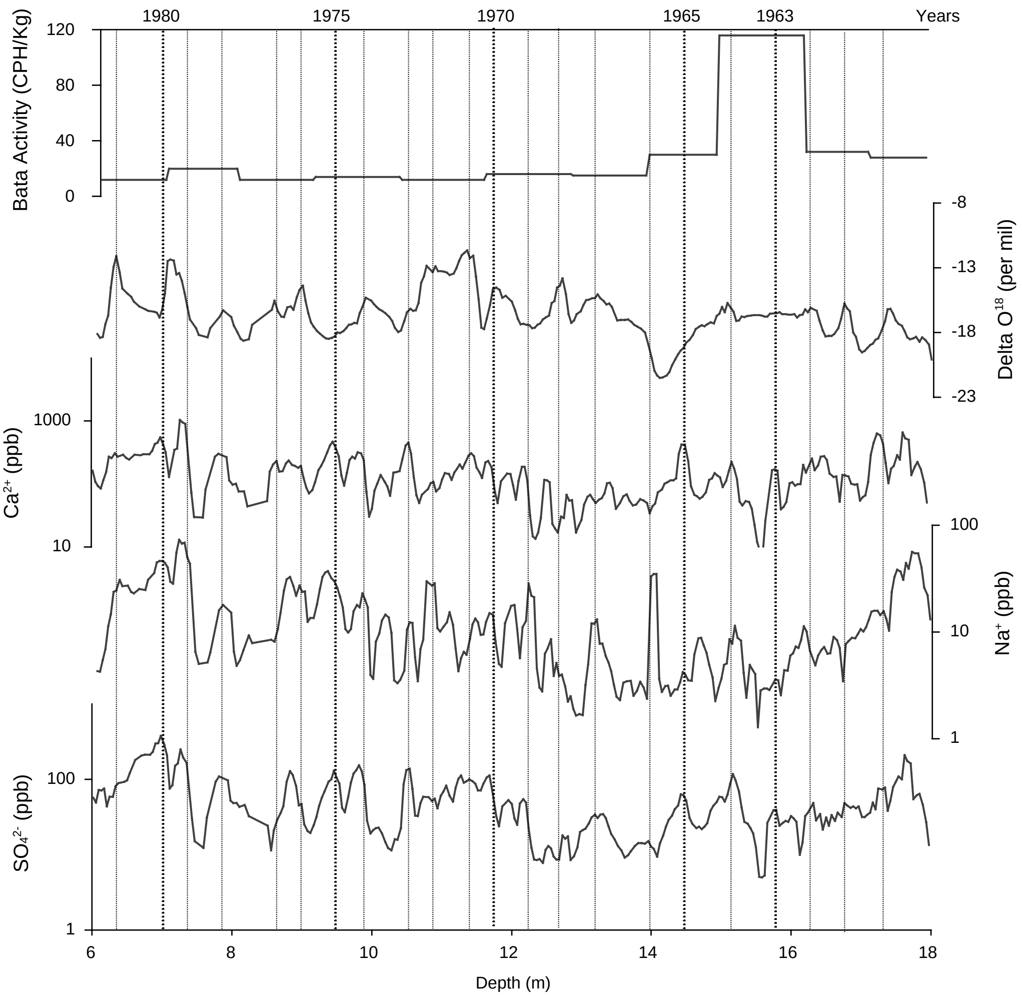
In order to investigate the inter-species relations and common structure within the ER glaciochemical data, we performed EOF analysis on the eight major ion (SO_4^{2-}, Mg^{2+}, Ca^{2+}, Na^+, Cl^-, NH_4^+, K^+, and NO_3^-) time-series. Here, multivariate EOF analysis is used rather than repeated simple linear regressions because EOF analysis allows a more robust assessment of the behavior of several variates and also provides new time-series that represent their relationships. EOF decomposition provides objective representations of multivariate data through the analysis of the covariance structure of its variates (Meeker et al., 1995). The EOF association for the ER ice core (named EOF-ions) is summarized in Table 1.

EOF 1-ions accounts for 58% of the total variance in the major ion series, and most of the major ions (except NH_4^+ and K^+) are strongly loaded on EOF1-ions. A comparison of EOF1-ions to selected chemical species (Fig. 3) shows that it captures the majority of the signal structure in these ion time-series. The strong association among 6 (SO_4^{2-}, Mg^{2+}, Ca^{2+}, Na^+, Cl^-, and NO_3^-) of the 8 species suggests that most of the major ions have a common source, which is most probably crustal aerosols derived from the arid dust producing regions over central Asia (Wake et al., 1994b; Kang et al., 2001b; Kreutz and Sholkovitz, 2000). K^+ and Cl^- dominate EOF2-ions with little loading on the other crustal species. This is indicative of a unique source or unique transport pathway for a portion of the K^+ and Cl^-. Fig. 4 shows that EOF2-ions trap a portion of the signal structure in the K^+ and Cl^- time-series. EOF3-ions is loaded primarily on NH_4^+ reflecting its unique biogenic source related largely from agricultural activity (Mayewski et al., 1983; Davidson et al., 1986; Wake et al., 1994b; Shrestha et al., 1997). Here, we focus on the first two of the EOF time-series (EOF1-ions and EOF2-ions) which represent two groups of ER ice core crustal species that are transported from different source regions or by different pathways. We compare these series with SLP over Asia and investigate their environmental significance.

3. Sea level pressure-ice core calibration

To investigate the relationship between EOF-ions series and atmospheric circulation, monthly instrumental records (1899–1996) of atmospheric SLP over the Northern Hemisphere (Trenberth and Paolino, 1980; Meeker and Mayewski, 2002) were chosen to compare with the ER glaciochemical time-series. Our investigation is based on the identification of a strong relationship between annual EOF-ions series (re-sampled from the raw series) and these monthly SLP data set. To explore relationships among the annually resolved EOF-ions series and monthly SLP fields, the 98 years of common SLP observation are divided into three groups according to the annual EOF-ions series: 33 years of lowest, 33 years of highest, and 32 years of intermediate values. Detailed methods for this analysis are described by Meeker and Mayewski (2002). Division into groups on this scale results in a conservative estimate of the SLP/EOF-ions relationship, since only the most persistent features of the SLP fields associated with EOF-ions are expected to appear in the 33-year averages (Meeker and Mayewski, 2002). Results of this analysis (Fig. 4) reveal that EOF-ions display strong connections to winter (January) and summer (July) SLP over Eurasia which is the primary source for most species in the Himalayas.

EOF1-ions series are mainly influenced by two semi-permanent features of the winter SLP field over Eurasia (Fig. 5B–D). Winters in which EOF1-ions series are lowest (Fig. 5B) exhibit high pressure anomalies in the region of the Siberian High (SibHi) and low pressure anomalies in the Mongolian High (MongHi). This pattern is reversed in winters in which EOF1-ions series are highest and low pressure anomalies exist for the



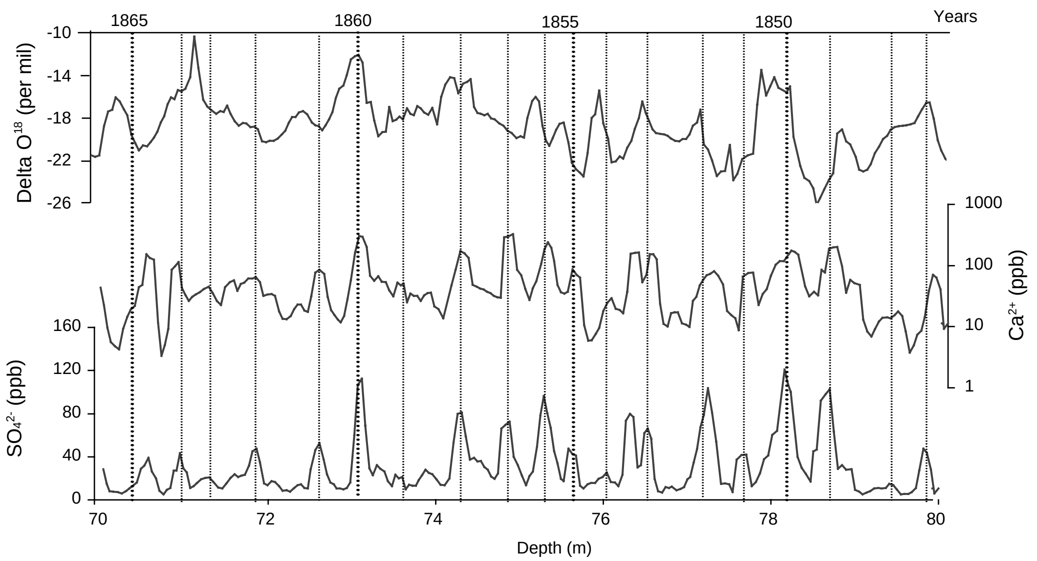


Fig. 2. Top: A sample of the upper ER ice core dating using selected chemical species (at the depth of 6–18 m). The 1963 bomb peak is clearly visible in the beta activity records. Bottom: A dating sample for the ice core section close to the bottom (at the depth of 70–80 m). Dashed lines represent annual boundaries.

Table 1
Results from empirical orthogonal function (EOF) analysis of major ion time-series. The numbers in the table represent the percent of variance associated with each major ion. Negative values indicate an inverse relationship. Total numbers represent the percent of total variance in the major ion records explained by each EOF

	EOF1-ions	EOF2-ions	EOF3-ions
Na^+	70.5	7.7	−3.5
NH_4^+	29.4	−5.6	59.6
K^+	27.1	49.4	4.1
Mg^{2+}	76.3	−6.7	−3.1
Ca^{2+}	69.2	−8.7	−4.5
Cl^-	51.9	41.7	0.0
NO_3^-	64.0	−10.0	1.1
SO_4^{2-}	75.7	−5.9	−1.5
Total	58.0	17.0	9.7

SibHi and high pressure anomalies for the MongHi (Fig. 5C). Comparison of the means January SLP fields for the 33 highest and 33 lowest EOF1-ions years (Fig. 5D) shows that winters with high EOF1-ions series have a steeper pressure gradient (>6 mb). The mean SLP field in summer over Eurasia displays a simple model such that low pressure exists throughout southern Asia (Fig. 5E). EOF2-ions series are strongly associated with pressure anomalies over Mongolian regions. We name this feature the Mongolian Low (MongLow). Summers in which EOF2-ions series are lowest exhibit low pressure anomalies (Fig. 5F), and, summers in which EOF2-ions series are highest have high pressure anomalies over Mongolia (Fig. 5G).

To explore relationships suggested by SLP difference fields in Fig. 5, we found, within those regions identified by the high–low SLP fields, those grid cells whose SLP records are most strongly associated with EOF-ions series. The January and July SLP series from the $5 \times 5°$ grid cells thus identified (blackened area in Fig. 1) were chosen to provide SLP histories throughout the instrumental period for the region (Fig. 6). We focus on the relationships between EOF-ions and the Mongolian SLP.

4. Relationships between glaciochemical series and atmospheric circulation

In order to compare the ER glaciochemical records with SLP series over the Mongolian region, EOF analysis was performed to emphasize the common features between EOF-ions and SLP series. In the case of two series (EOF-ions and SLP), EOF analysis results in a decomposition expressing the similarity (positive correlation) and dissimilarity (negative correlation) between the two. Our EOF analysis indicates that 57% of the variance in EOF1-ions and MongHi series is represented by their common first EOF (EOF1a) (positive correlation). The close correspondence between EOF1-ions and MongHi series, as well as the common component EOF1a series is shown in Fig. 6A. Similarly, EOF2-ions and MongLow series share 61% of their variance in their common first EOF (EOF1b) (positive correlation). Fig. 6B shows the comparison of EOF2-ions and MongLow with their EOF1b series.

A positive relationship exits between EOF1-ions and MongHi series. Generally, increases in EOF1-ions correspond to higher MongHi SLP (enhanced MongHi) in winter (e.g. during the 1930s and 1980s). During the 20th century, both EOF1-ions and MongHi series display an increasing trend and reach their highest value in the 1980s. As discussed before, EOF1-ions time-series may represent variations of the majority of the crustal species (e.g. SO_4^{2-}, Mg^{2+}, Ca^{2+}, and Na^+) in the ER ice core (Fig. 3 and Table 1) and can be considered as a proxy for the primary atmospheric dust transport over the Mt. Everest region. Investigation of the chemistry of snow, ice, and aerosol samples collected from glacier basins in the mountains of central Asia indicates that the spatial variation of crustal species is controlled primarily by the influx of desert dust derived from the vast arid regions of Asia (Fig. 1). In general, concentrations of crustal species decrease from the north to the south over central Asia as the distance from the arid regions increases (Wake et al., 1990, 1994b; Shrestha et al., 1997; Sun et al., 1998; Kreutz and Sholkovitz, 2000). Crustal species in Himalayan snow/ice are also influenced by dust aerosols transported southward from arid regions over central Asia (i.e. Taklamakan Desert and Qaidam Basin) (Wake et al., 1993, 1994a; Kang et al., 2000). A stronger MongHi strengthens southward surface winds (Murakami, 1987) allowing more dust aerosols to be transported from these desert regions of central Asia to the Himalayas. Vice versa a weakened MongHi corresponds to lower concentrations of crustal species in the ER ice core. We conclude that changes in concentration of the majority of the crustal species in ER ice core are related to variations in the strength of the winter MongHi.

The close correspondence between EOF2-ions and summer MongLow series as well as their common component EOF1b series is shown in Fig. 6B. Increases in EOF2-ions series correspond to higher SLP over Mongolia in summer (weaker MongLow). A dramatic example occurs around the 1920s (weaker MongLow and higher EOF2-ions). Inversely, decreases in EOF2-ions series correspond to lower SLP over Mongolia (deeper MongLow), such as during the 1930s. In general, EOF2-ions display a decreasing trend since the MongLow has been enhancing during the 20th century. As noted earlier, the EOF2-ions series likely

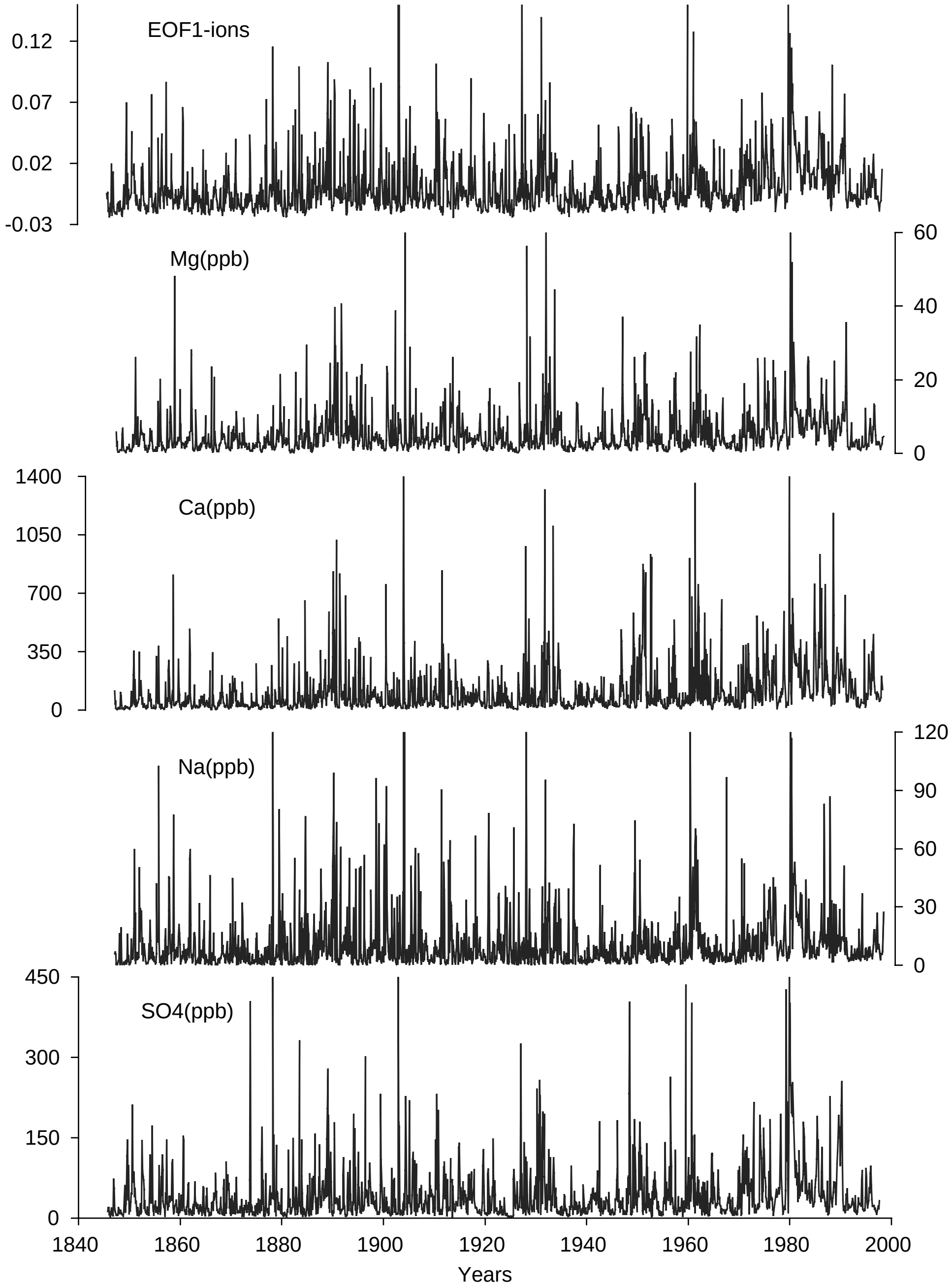


Fig. 3. Comparison of the first EOF (EOF1-ions) to selected ER major ion time-series (original sampling).

represents the minority of the crustal species in the ER core and is related to KCl-rich deposits which have a unique source/transport pathway that differs from the majority of the crustal species in the ER core. Although the sources of the KCl-rich deposits cannot be specified, a possible source for these EOF2-ions species may be local or regional (around the north and south of Himalayas) mineral aerosols (Shrestha et al., 1997; Thompson et al., 2000) that are deposited mainly during the summer season which we assume because of their connections to summer atmospheric circulation (MongLow).

The relationship between EOF2-ions and summer MongLow series can be explained by considering the summer Indian Monsoon (South Asian Monsoon). The MongLow (a part of the summer Asian Low) is related to the strength of the Indian Monsoon and a deeper MongLow corresponds to a stronger Indian Monsoon

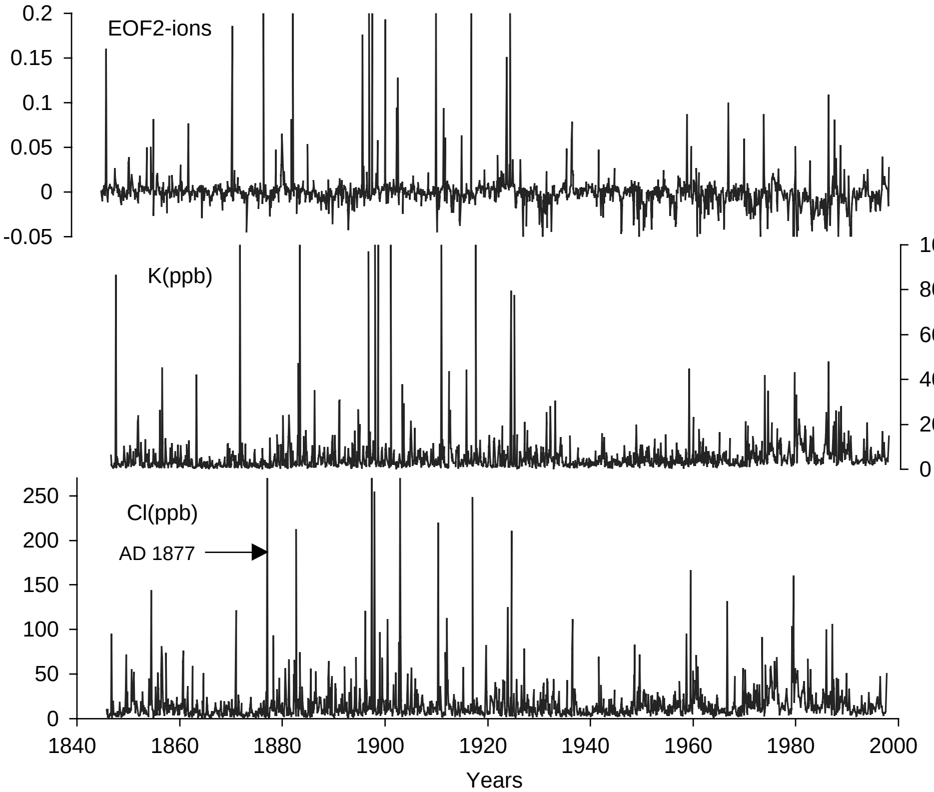


Fig. 4. Comparison of the second EOF (EOF2-ions) to selected ER major ion time-series (original sampling).

(Webster and Yang, 1992; Tang, 1998). As the summer MongLow deepens, the Indian Monsoon strengthens bringing more monsoon precipitation over the southern Tibetan Plateau and the Himalayas. This reduces the loading of summer atmospheric dust aerosols in the region. Inversely, a higher MongLow SLP in summer, corresponds to a weaker Indian Monsoon, favoring more dust aerosol deposition on the glaciers of Mt. Everest. Recent work from the Dasuopu ice core verifies that this ice core record is sensitive to fluctuations in the intensity of the Indian Monsoon through the demonstration that reductions in monsoonal intensity are related to higher dust and chloride concentrations (Thompson et al., 2000). A very good example is the high Cl^- concentration in 1876–1877 recorded in both the Dasuopu and the ER ice cores corresponding to a major Indian Monsoon failure. Therefore, EOF2-ions represent the summertime dust aerosol and are also related to variations in the intensity of the Indian Monsoon.

5. Conclusions

The historical glaciochemical records covering the period AD 1846–1997 are reconstructed from an 80.4 m ER ice core on the northern slope of Mt. Everest. EOF analysis of the eight major ion (SO_4^{2-}, Mg^{2+}, Ca^{2+}, Na^+, Cl^-, NH_4^+, K^+, and NO_3^-) time-series is performed to investigate the inter-species relations and common structure within the ER glaciochemical data. EOF associations indicate that most of the major ions (except NH_4^+ and K^+) are strongly loaded on EOF1-ions (58% of the total variance). EOF2-ions (17% of the total variance) are loaded primarily on K^+ and Cl^- indicating a unique source/transport pathway for a portion of K^+ and Cl^- in the ER core. We focus on the instrumental SLP over Asia to explore the relationships between EOF-ions variations and atmospheric circulation.

A positive relationship exists between EOF1-ions and MongHi series suggesting that an enhanced MongHi strengthens the transport of dust aerosols southward, from arid regions over central Asia, to Mt. Everest during the winter season. Both the concentrations of the majority of the crustal species in ER ice core and the SLP of MongHi have increased since the early 20th century and highest values occur around the 1980s. The close correspondence between EOF2-ions and the summer MongLow indicates that a deeper MongLow (lower SLP of MongLow), which is related to a stronger Indian Monsoon, contributes to a decrease in summer dust aerosols. Generally, the MongLow has deepened

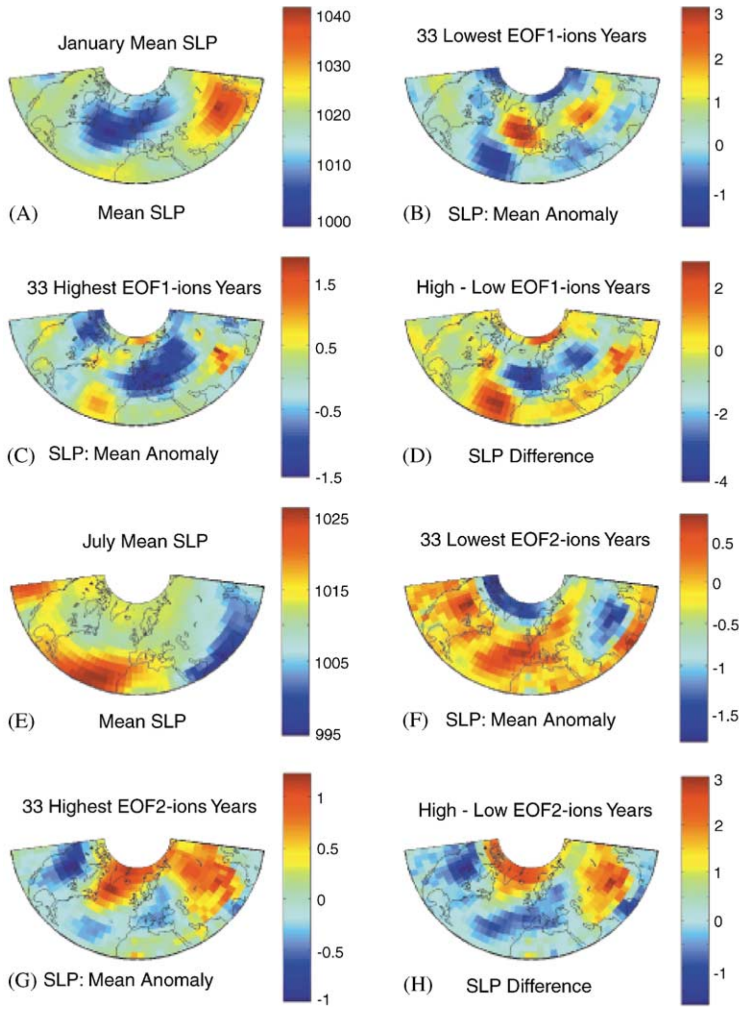


Fig. 5. Mean sea level pressure (SLP) field 1899–1996. (A) Mean January SLP field 1899–1996; (B) mean SLP field anomaly in January for 33 years of lowest EOF1-ions values; (C) mean SLP field anomaly in January for 33 years of highest EOF1-ions values; (D) difference SLP field in January: mean of highest 33 years—mean of lowest 33 years; (E–H) same as (A–D) but for July and EOF2-ions.

and summer dust deposits have decreased since the 1920s.

The winter dry season (with high aerosol concentrations) and the summer wet season (with low aerosol concentrations) dominate atmospheric and aerosol behavior over the Tibetan Plateau (Wake et al., 1994b; Shrestha et al., 2000; Kang et al., 2000). ER ice core records comprise two kinds of crustal species which are transported from different source regions and are deposited on the glacier in different seasons. EOF1-ions represent the majority of the crustal species in the core and are related to winter atmospheric circulation. These species are mainly transported from arid regions and central Asia during the winter dry season. EOF2-ions represent the remainder of the crustal species in the core and are related to summer atmospheric circulation. They are mainly from local/regional (around the north and south of Himalayas) dust aerosols produced during the summer season. Thus, ice core records from ER glacier may provide a unique opportunity to investigate changes in atmospheric circulation over Asia in the past.

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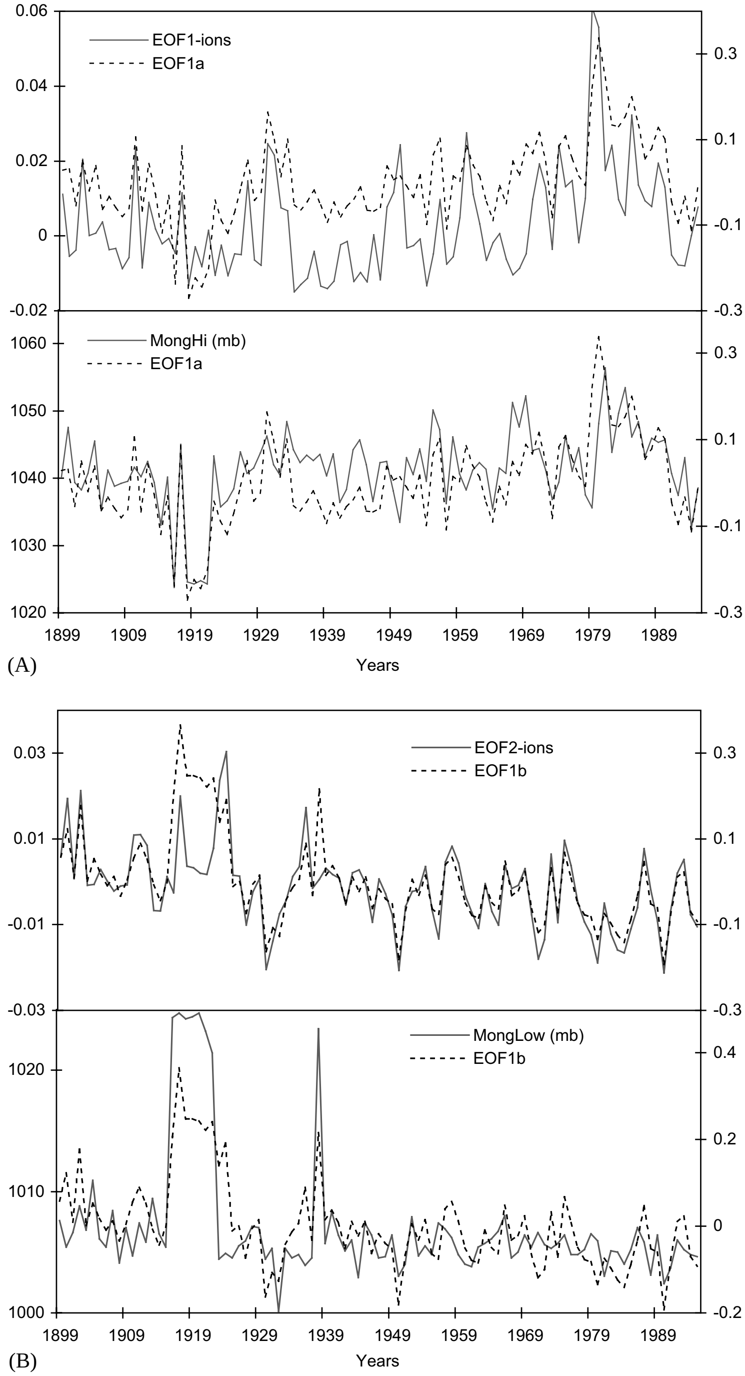

Fig. 6. (A) Plots of annual EOF1-ions, January Mongolian High (MongHi) (50°N, 95°E) SLP and their common first EOF (EOF1a); (B) plots of annual EOF2-ions, July Mongolian Low (MongLow) (50°N, 95°E) SLP and their common first EOF (EOF1b).

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